Parameter Optimization of a Snake Robot Using Taguchi Method

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Abstract— **In this paper, performance of a 16 link snake robot in serpentine locomotion is investigated. Key kinematics and dynamics parameters are identified. The aim of this paper is to minimize average power consumption per unit distance traveled. Dynamic and kinematics equations of snake robot are used to perform simulation and obtain results. Key kinematics parameters are identified. Taguchi method is utilized and orthogonal array table is constructed. ANOVA technique is used to analyze the statistical significance of kinematic and dynamic parameters. Taguchi method is used to determine optimum parameter settings effecting performance of snake robot. Finally, the snake robot is modeled in WEBOTS software and forward motion is obtained.**

Keywords-snake robots; Taghuchi method; ANOVA techniqu; consumption energy; distance travel

I. INTRODUCTION

Snake robots were first introduced by Hirose [1]. Since then a lot of snake robots are designed. Snake robots may be designed to move in water and land [2]. Serpentine movement is one of the quickest and most common locomotion of real snakes. Locomotion is accomplished by propagating a wave in the form of the serpenoid curve throughout the snake robot. In other words, locomotion is only accomplished through shape changing, like a real snake. Hirose understood that main basis for forward propulsion, using the serpentine gait, is anisotropy in the friction coefficients between the lateral and tangential frictions. Therefore, he used small wheels in direction of links which are placed on the bottom of them. Bayraktaroglu [3] presented a new way for producing body shape of snake robot which uses circles with constant radius and polynomial functions. Conkur [4] considered the trajectory of snake robot. Lio [5] optimized the serpenoid curve by using Genetic Algorithm (GA) and presented a new trajectory for snake robot. Ma et al [6] proposed serpentine curve and showed that this curve is very similar to serpenoid curve. Hasanzadeh and Akbarzadeh [7] presented a novel gait, forward head serpentine (FHS), for a two dimensional snake robot. In their work, GA was used to find FHS gait parameters and results were validated using experiments. Hasanzadeh and A. Akbarzadeh [8] applied GA to optimize CPG-network parameters of a snake robot in order to achieve maximum robot speed. Next, they found relations between optimal CPG-network parameters and environmental conditions for snake robot with different numbers of links. Then they proposed a new method that can be used with a controller to provide instantaneous changes in environmental conditions. They also generated a novel gait, FHS gait, for snake robot [9]. By using the proposed gait, the head of snake robot always remains in the general direction of motion.

This paper is organized as follows: first kinematics and dynamics of a snake robot are described to obtain distance travelled and consumption energy. To find the optimum kinematics and dynamics parameters of a 16 link snake robot, Taguchi method is applied. Effects of parameters and optimum levels of them are determined and the results are confirmed. Finally, WEBOTS software is used to simulate.

II. SNAKE ROBOT MODEL

The serpenoid curve is used for generating serpentine locomotion. The curvature function is defined as follows

$$\rho(s) = -\frac{2K_n\pi}{L}\sin(\frac{2K_n\pi s}{L}) \quad (1)$$

Where L is the total length of snake robot, K_n is the number of undulation, α is the initial winding angle and s is the body length along the body curve, as shown in Fig. 1.

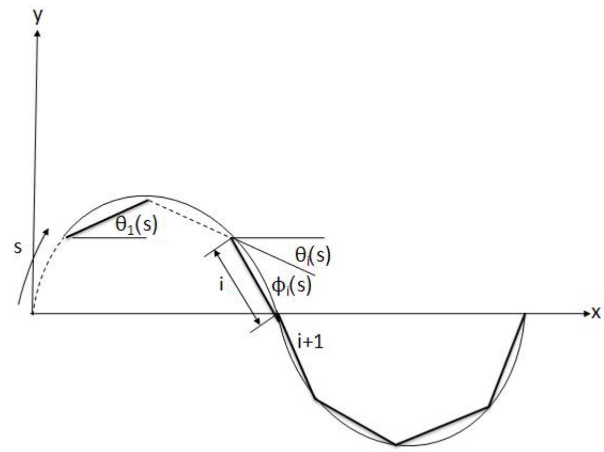

Figure 1. Scheme for fitting the serpenoid curve

Since $s = \frac{1}{\rho}\varphi$, so we have

$$d\varphi = \rho\, ds = \int_{s+(i-1)l}^{s+il} \frac{-2K_n\pi\alpha}{L}\sin(\frac{2K_n\pi u}{L})du \quad (2)$$

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After simplifying, the relative angles are obtained as follows:

$$\varphi_i(s) = -2\alpha\sin(\frac{k_n\pi}{L})\times\sin(\frac{2k_n\pi s}{L}+\frac{2k_n\pi i}{n}-\frac{k_n\pi}{n}) \quad (3)$$

Where n is the number of links and l is the unit length of link. Relative value of angle velocity and angle acceleration can be deduced:

$$\dot{\varphi}_i(s) = \frac{-4\alpha k_n\pi}{L}\sin(\frac{k_n\pi}{L})\times\sin(\frac{2k_n\pi s}{L}+\frac{2k_n\pi i}{n}-\frac{k_n\pi}{n})\dot{s} \quad (4)$$

$$\ddot{\varphi}_i(s) = \frac{-4\alpha k_n\pi}{L}\sin(\frac{k_n\pi}{L})\times\sin(\frac{2k_n\pi s}{L}+\frac{2k_n\pi i}{n}-\frac{k_n\pi}{n})\ddot{s} - \frac{8\alpha k_n^2\pi^2}{L^2}\sin(\frac{k_n\pi}{L})\times\sin(\frac{2k_n\pi s}{L}+\frac{2k_n\pi i}{n}-\frac{k_n\pi}{n})\dot{s}^2 \quad (5)$$

From Fig. 2, the relation between relative angle and absolute angle is obtained as,

$$\theta_i = \theta_1 + \sum_{k=1}^{i-1}\varphi_k \quad (6)$$

$$\dot{\theta}_i = \dot{\theta}_1 + \sum_{k=1}^{i-1}\dot{\varphi}_k \quad (7)$$

$$\ddot{\theta}_i = \ddot{\theta}_1 + \sum_{k=1}^{i-1}\ddot{\varphi}_k \quad (8)$$

Where θ_1, $\dot{\theta}_1$ and $\ddot{\theta}_1$ are the absolute value of joint angles, angle velocity, and angle acceleration of i^{th} link with respect to the x-axis, respectively. Obviously, by consider fig. 2, the kinematic of snake robot can be easily obtained. Also position, velocity and acceleration of snake robot can be calculated as follows:

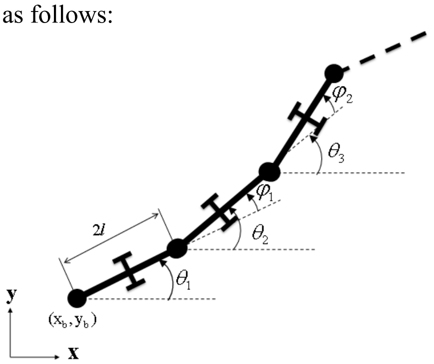

Figure 2. Schematic of snake robot

$$x_{ci} = x_b + \sum_{j=1}^{i-1} l_j\cos\theta_j + d_i\cos\theta_i \quad (9)$$

$$y_{ci} = y_b + \sum_{j=1}^{i-1} l_j\sin\theta_j + d_i\sin\theta_i \quad (10)$$

Where (x_b, y_b) is coordinate of the end of tail link. It should be mentioned that, by knowing position and absolute angle of tail link, the framework of snake robot can be determined. The generalized coordinate are selected as follows

$$q_j = [\theta_1, \theta_2, ..., \theta_n, x_b, y_b] \quad (11)$$

And the equation of motion can be written as

$$\frac{d}{dt}(\frac{\partial K}{\partial \dot{q}_i}) - \frac{\partial K}{\partial q_i} + \frac{\partial V}{\partial q_i} = Q_i^{nc} \quad (i = 1,2,..n+2) \quad (12)$$

Where K is kinematic energy, Q_i^{nc} is non-conservative forces and V is potential energy. Actuators torques and friction forces are non conservative forces. During locomotion, the center of gravity of each link remains on the ground. Therefore, the potential energy will be zero. By solving the Lagrangian formulation [7, 10], the dynamic model for snake robot can be derived as:

$$B\tau = M(\theta)\ddot{q} + H(\theta,\dot{\theta}) + F(\theta) \quad (13)$$

where M(θ) is the (n+2)×(n+2) positive definite and symmetric inertia matrix, $H(\theta,\dot{\theta})$ is the (n+2)×1 matrix related to centrifugal and Coriolis terms, F(θ) is an (n+2)×1 matrix related to frictional forces, B is an (n+2)×(n-1) constant matrix. τ is (n-1)×1 matrix, represent input torques and $q, \dot{q}, \ddot{q}$ are (n-1)×1 matrix of generalized coordinates and their derivatives. $\theta, \dot{\theta}$ and $\ddot{\theta}$ are n×1 matrix of links absolute angles and their derivatives. The average power consumption per unit distance (E) can be calculated as,

$$E = \frac{\sum_{i=1}^{n}\int_0^T \tau_i\omega_i}{L_{dis}} \quad (14)$$

Where T is simulation time, τ_i and ω_i represent the torques and the absolute velocity angle of the i^{th} link, respectively.

In order to achieve optimum performance of the robot, it is important to properly set the kinematics and dynamics parameters. The selected input parameters in this study and their levels of the snake-like robot are shown in Table 1. The selected response is the ratio of energy to the total distance traveled.

III. TAGUCHI METHOD

Dr. Genichi Taguchi has developed a method based on orthogonal array experiments that has much less needed experiments to reach an optimum setting of process control parameters. Thus, the Taguchi Method achieves the integration of design of experiments (DOE) with the parametric optimization of the process, resulting in the desired results. The orthogonal array (OA) provides a set of minimum experimental runs. In OA any two columns of an array form all combinations the same number of times. In order to evaluate optimal parameter settings, the Taguchi Method uses a statistical measure of performance called signal-to-noise ratio (S/N) which is logarithmic function of desired output. Taguchi's signal-to-noise ratios take both the mean and the variability into account. The S/N ratio is the ratio of the mean (signal) to the standard deviation (noise). The standard S/ N ratios generally used are Nominal is best (NB), lower the better (LB) and higher the better (HB). Since in the paper the lower value for Energy/Distance is better, therefore, the formula for lower the better is (15) and (16) are used.

$$LB = \frac{1}{n}(\sum (y_i)^2) \tag{15}$$

$$\eta_{ij} = -10 Log(L_{ij}) \tag{16}$$

The optimal setting is always the parameter combination which has the highest S/ N ratio regardless of the used type. The L32 Taguchi design and the calculated S/N ratios are shown in Table 2.

The ANOVA results are shown in Table 3. As shown in this table, all single factors are significant. The interaction between K_n and l is not statistically significant using 95% confidence level. Although all single factors are statistically significant, due to higher F-value, K_n is the most effective parameter while m is the least effective.

TABLE I. INPUT FACTORS AND THEIR LEVELS

Factor	Symbol	First level	Second level	Third level	Fourth level
length	l	0.08	0.1	0.12	0.14
angle	α_0 (rad)	0.4	0.5	0.6	0.7
mass	m (kg)	0.1	0.12	0.14	0.16
undulation	K_n	1	2	-	-

TABLE II. THE L_{32} TAGUCHI DESIGN AND THE CALCULATED S/N RATIOS

No. Exp.	K_n	l	m	α	Energy/distance	SNR
1	1	0.08	0.1	0.4	5.44	-14.71
2	1	0.08	0.12	0.5	6.15	-15.78
3	1	0.08	0.14	0.6	7.44	-17.43
4	1	0.08	0.16	0.7	10.96	-20.79
.	.	.	.	.	.	.
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.	.	.	.	.	.	.
29	2	0.14	0.1	0.6	24.06	-27.62
30	2	0.14	0.12	0.7	42.47	-32.56
31	2	0.14	0.14	0.4	25.17	-28.02
32	2	0.14	0.16	0.5	27.62	-28.82

TABLE III. ANOVA FOR SN RATIOS

Source	DF	SS	MS	F	P
K_n	1	2387.84	2387.84	8282.32	0
l	3	110.58	36.86	127.85	0
m	3	27.21	9.07	31.46	0
α	3	98.25	32.75	113.59	0
K_n *l	3	0.36	0.12	0.42	0.74
Residual Error	18	5.19	0.29		
Total	31	2629.43			

The graphical representation of the S/N ratios is shown in Fig 3. As shown in this figure, in order to get the minimum Energy/distance, lower level of K_n and m, higher level of l and the 2nd level of α, ($K_{n1}l_4m_1\alpha_2$) should be used.

For confirmation test the optimal values l=0.14, K_n=1, m=0.1 and α=0.5 are used in Matlab simulation program and the value of 2.58 for Energy/distance is obtained. Results are summarized in Table 4. The value for Distance/energy is improved from initial level of 5.4443 to 2.5817. This represents 52% improvement in robot performance.

To further study the snake robot, it is modeled in Webots simulation platform. Webots is a professional mobile robot simulation software package. Wheels are used at the bottom of each link of snake robot. Fig. 4 shows the simulation of snake robot with 16 links. As shown in this figure, forward progression is achieved.

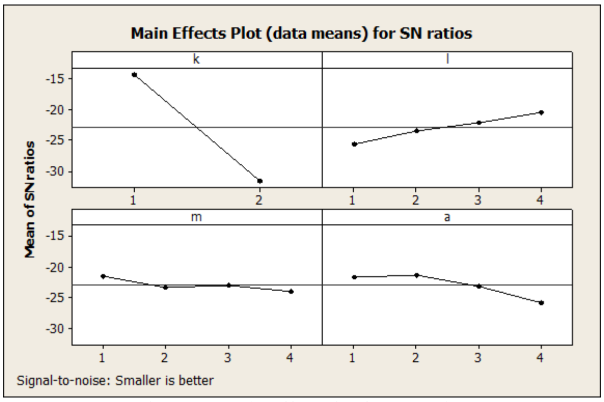

Figure 3. Main effect plot for SN ratios

TABLE IV. . TAGUCHI CONFIRM RESULTS

	Starting condition $l_1m_1K_{n1}\alpha_1$	Predicted value (ANOVA model) $l_4m_1K_{n1}\alpha_2$	simulation results (Dynamics model) $l_4m_1K_{n1}\alpha_2$
S/N ratio	-14.7189	-8.71014	-8.2381

Energy/Distance	5.4443	2.7259	2.5817

Improvement S/N ratio for Energy/Distance = 6.48 (dB)

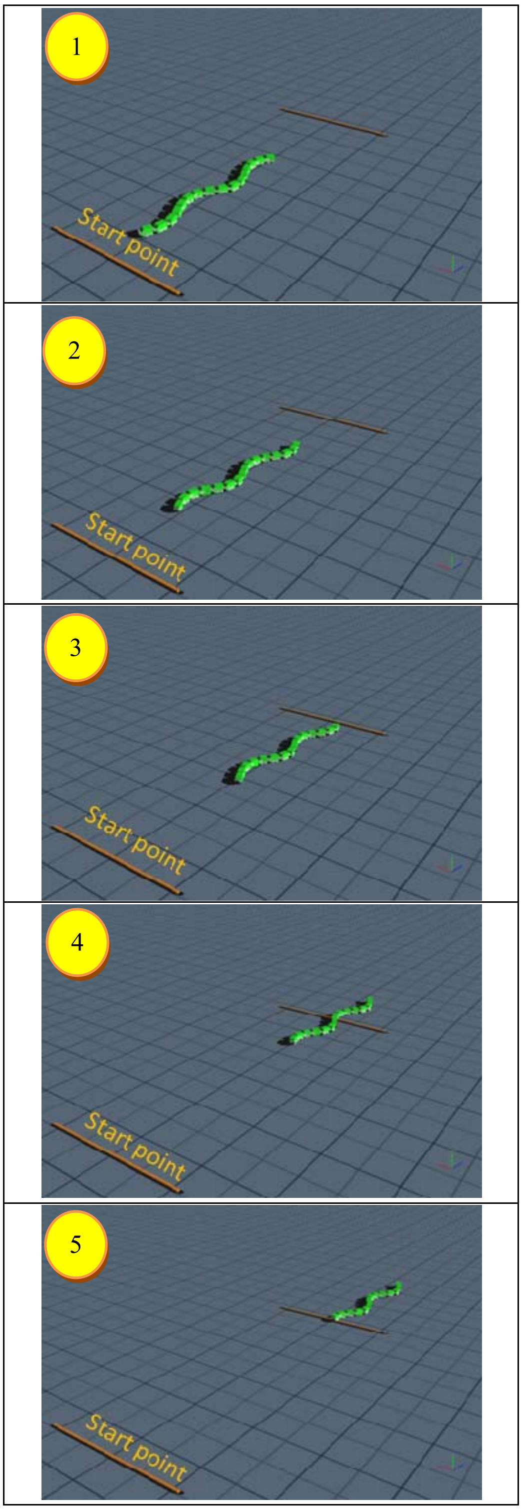

Figure 4. Simulation of snake robot in Webots

IV. CONCLUSTION

In this paper, effects of parameters settings on performance of a snake robot in serpentine locomotion are investigated. Dynamic and kinematics of snake robots are used in simulation and to obtain the performance results. Taguchi Method is utilized to find the optimum levels of *l*, α, *m* and K_n for a 16 link snake robot. The results show that the lowest level of *m* and K_n, highest level of *l* and an *α* value of 0.5 results in the highest Energy/Distance ratio. ANOVA results show that K_n is the most important factor and *m* is the least important factor. Using these results a 52% improvement in robot performance, energy/distance, is achieved. Finally, the snake robot is further modeled in WEBOTS software to demonstrate forward progression. These results can be utilized by a designer as guidelines for mechanical design of the snake robot. For future works, effects of number of the links on the performance of the snake robot will be investigated.

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